Ocean circulation I

Reading: GPC Ch 7

Outline

- Oceans and climate
- Properties of seawater
- Vertical structure of the ocean
- Mixed layer
- Wind-driven ocean circulation - example - subtropical gyre

The ocean general circulation and climate

Importance of ocean to climate:

It is wet, has low albedo, large heat capacity, and it is fluid

- Oceans receive more than half the energy entering the climate system
- Primary source for water vapor and heat for atmosphere (evaporation, cooling) - hence, it drives the hydrological cycle
- Provides bulk of thermal inertia of climate system from weeks to centuries and longer
- Great capacity of storing heat in summer and releasing it in winter – hence, it reduces the magnitude of the seasonal T cycle
- Carries heat over long distances: in particular, it helps reduce the equator-to-pole temperature gradients
- Ocean heat transport also changes the local sea surface temperature (SST) that may change regional climate. The tropical atmosphere is in particular strongly coupled to the ocean surface
- Is a reservoir for chemical elements. In particular, oceans are important in the carbon cycle
- Sea salt particles act as cloud condensation nuclei

Composition of the ocean

- 96.5% water
- 3.5% dissolved salts (primarily), particles, organic material and gases
- **salinity = S** = salt content of water mass by weight. Usually reported in parts per thousand ('per mil')
- Typical ocean salinity: 35 per mil (range: 25-40 per mil)
- Ion ratios remarkably constant, but overall salinity not

Salt Content of the Earth's Oceans

Salt Ion	*Grams per Kilogram (g/kg) of Ion in Seawater*	*Ion by Weight (%)*
Chloride (Cl^-)	18.980	55.04
Sodium (Na^+)	10.556	30.61
Sulfate (SO_4^{2-})	2.649	7.68
Magnesium (Mg^{2+})	1.272	3.69
Calcium (Ca^{2+})	0.400	1.16
Potassium (K^+)	0.380	1.10
Bicarbonate (HCO_3^-)	0.140	0.41
Bromide (Br^-)	0.065	0.19
Boric acid (H_3BO_3)	0.026	0.07
Strontium (Sr^{2+})	0.013	0.04
Flouride (F^-)	0.001	0.00
Total	34.482	99.99

Source: PINET, P. R., *Oceanography*, St. Paul, MN: West Publishing Co., 1992.

Differences between seawater and freshwater

property	freshwater	seawater
freezing pt	0 C	-1.8C extrudes salts when freezing
typical density	1000 kg m^{-3}	1026 kg m^{-3} (1020- 1029 kg m^{-3})
density	depends on T, P densest at ~4 C	depends on T, S, P the colder the denser
	Water almost incompressible, little dependence on p	

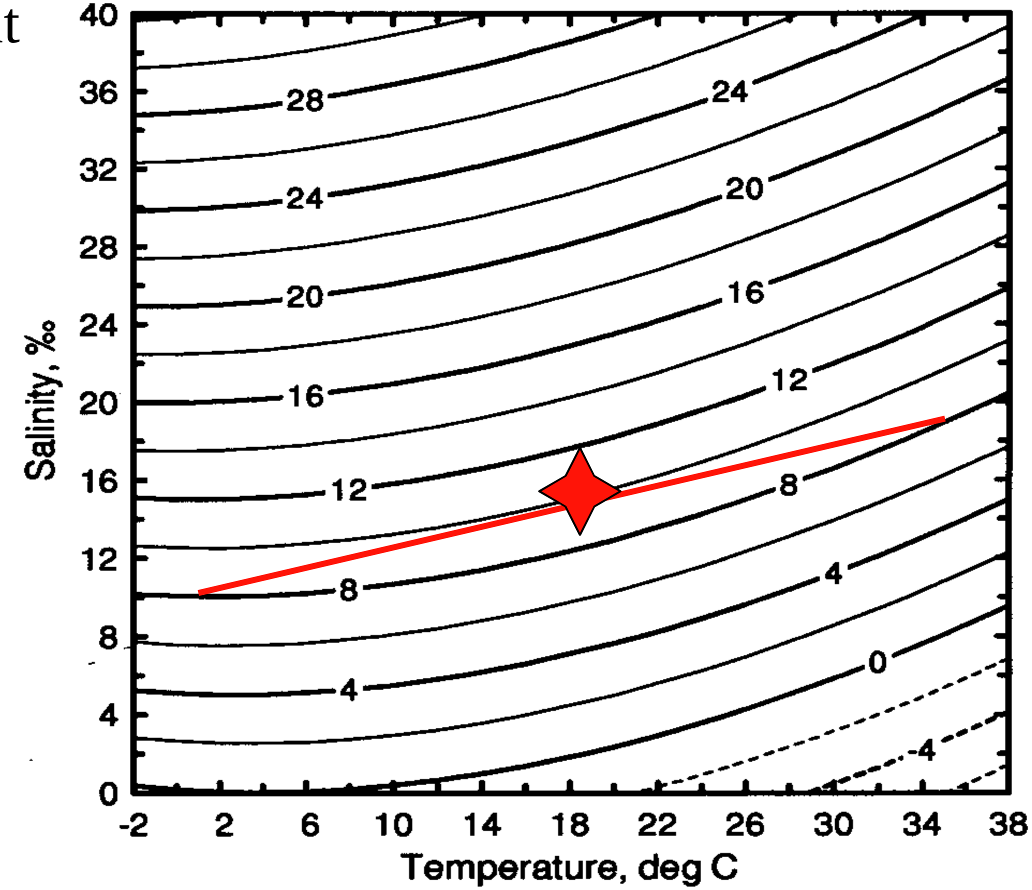
T=temperature, S=salinity, P=pressure

Seawater density

•Density of seawater is determined by ***salinity(S) and temperature(T)***
•Density increases with decreasing temperature
•Density increases with increasing salinity
•Typical range for temperature: -2 to 30 degrees C
(average T of world ocean 3.6 C)
•Salinity range for seawater: 25-40 ‰; typically 34-35 ‰
•Unlike air, water is fairly incompressible, so density ρ remains close to 1000kg/m^3 even at depth. As a consequence, density is usually reported as a deviation from 1000kg/m^3, i.e.: ρ-1000kg/m^3 (density in the next slide is reported in this way)
•***Potential density*** is the density that the seawater would have if it was at the ocean surface (i.e. same pressure as atmospheric pressure)

This shows how the ***density of seawater*** depends on salinity and temperature. Note the nonlinear T dependence, which gives seawater an interesting property: if you mix two waters of the same density but different T and S properties (the two ends of the red line), the ***mixed water (the red cross in the middle) will have a higher density than its parent waters***. This process is thought to be important for sinking of water at high latitudes when salty but less cold waters from ocean currents mix with cold fresh waters to produces even denser waters that sink.

Note that ~1 **‰** change of S has similar effect on density as ~4 degree temperature change (for typical ocean T and S values).



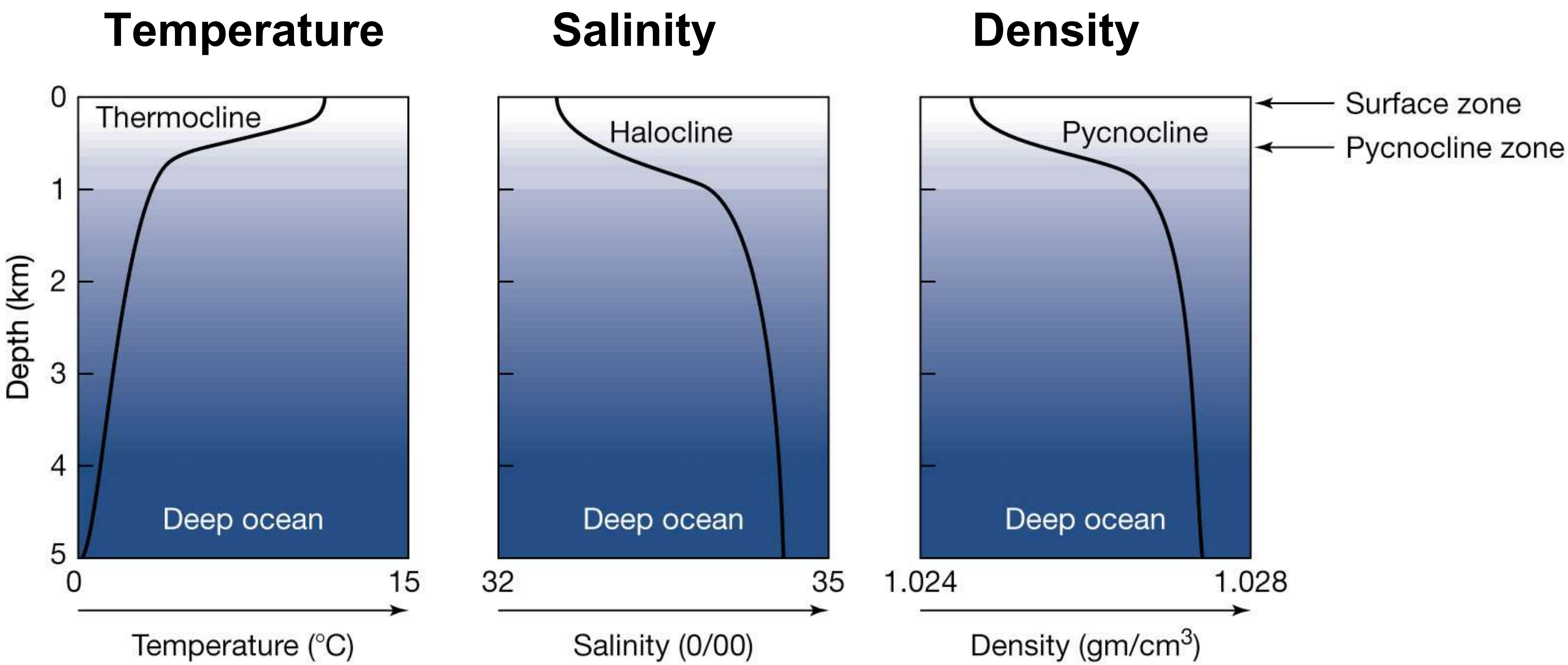
Freezing seawater

Another interesting property is that unlike fresh water that is most dense around 4 degrees C, seawater (with salinity larger than 24.7‰) becomes increasingly denser with cooler temperatures until it freezes. This means that to freeze seawater (assuming the column of seawater is well mixed and sufficiently salty), the entire column needs to be frozen (can you see why?).

High latitude sea ice forms (without having to freeze the entire column of water) because there is a fresh water layer near the surface. This causes a decrease in density that offsets the increase associated with colder temperatures near the surface, allowing water near the surface to freeze while warmer water is present below.
Arctic water is fresh because P>E there, and also there is input from Arctic rivers into the Arctic basin.

Typical vertical structure of the ocean

(varies with latitude, especially in the first 1000 m)



A ‘cline’ is a sharp vertical gradient - hence ‘thermocline’ and ‘halocline’.

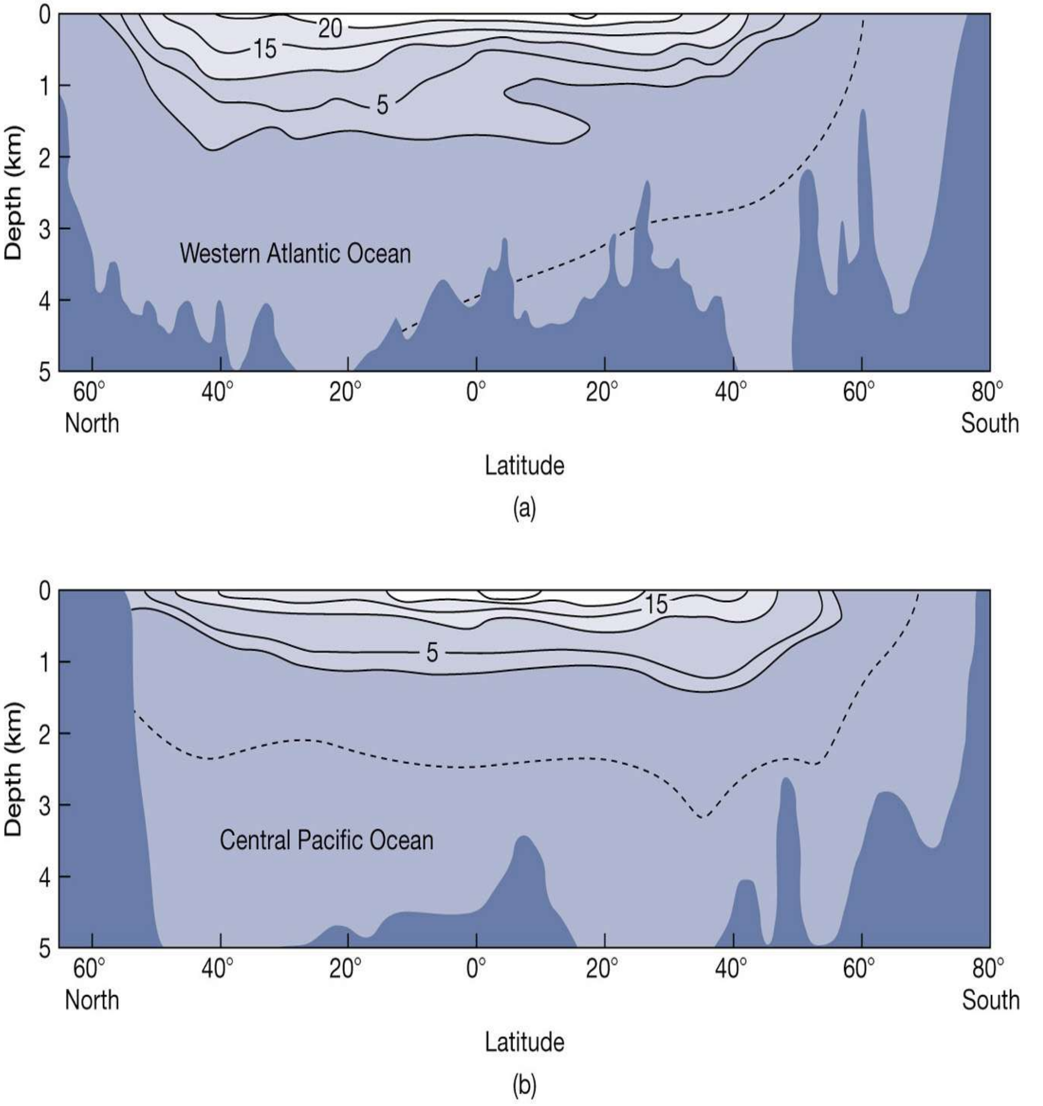
The pycnocline separates the **surface zone (aka mixed layer)** from the **deep ocean.**

Vertical structure of temperature in the ocean (T in C)

Mixed layer **-** first ~200m or so of the ocean, where there is strong vertical mixing and hence the water properties (T,S) are roughly uniform.

Thermocline **-** region of sharp temperature drop with depth, demarking the boundary between the mixed layer and the interior ocean.

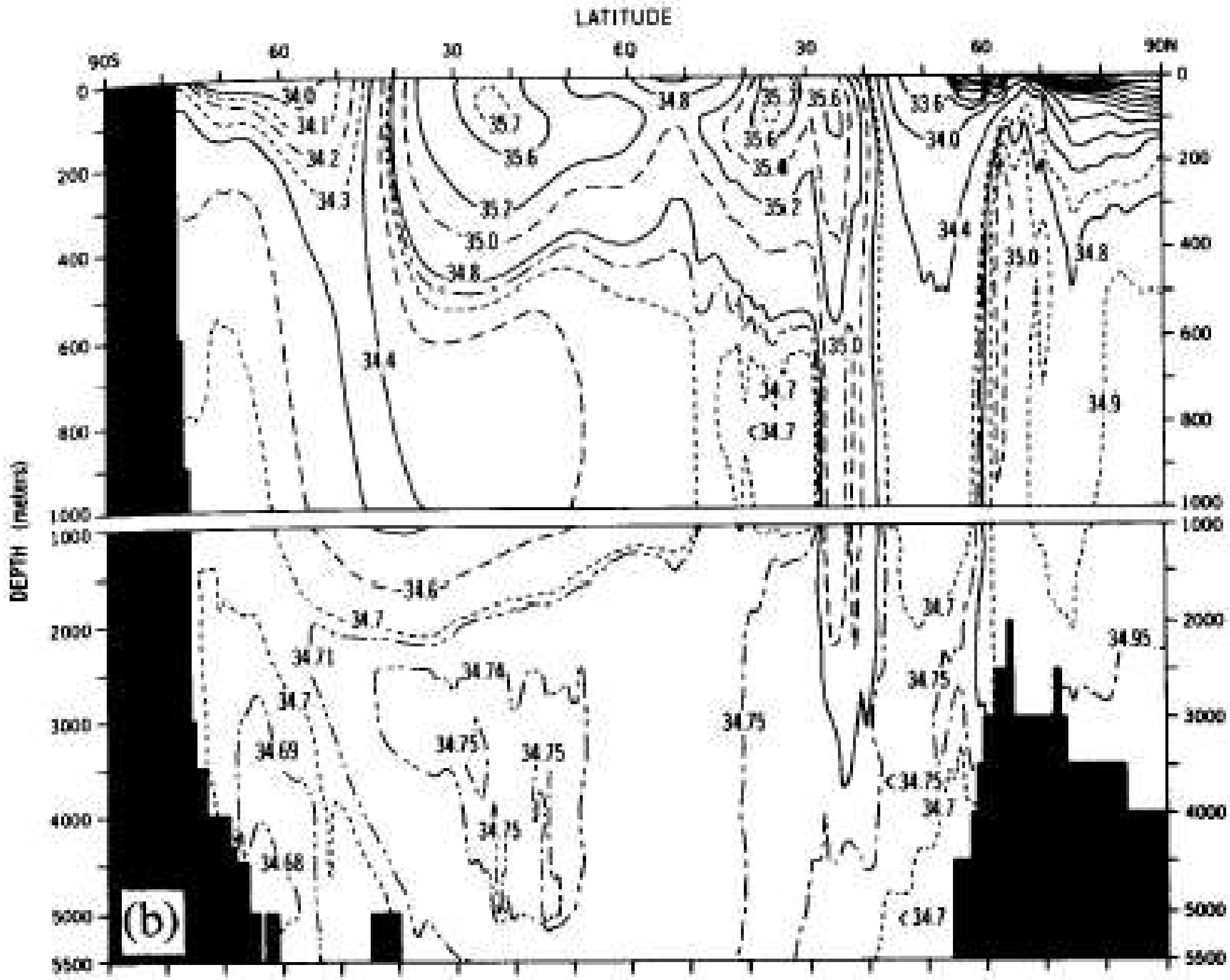
Note that most of the interior ocean has a fairly uniform temperature.



Annual mean zonal average

Salinity structure: annual mean zonal average

Note the match between the surface salinity and atmosphere P – E. Sharp gradients in salinity are known as **haloclines.**

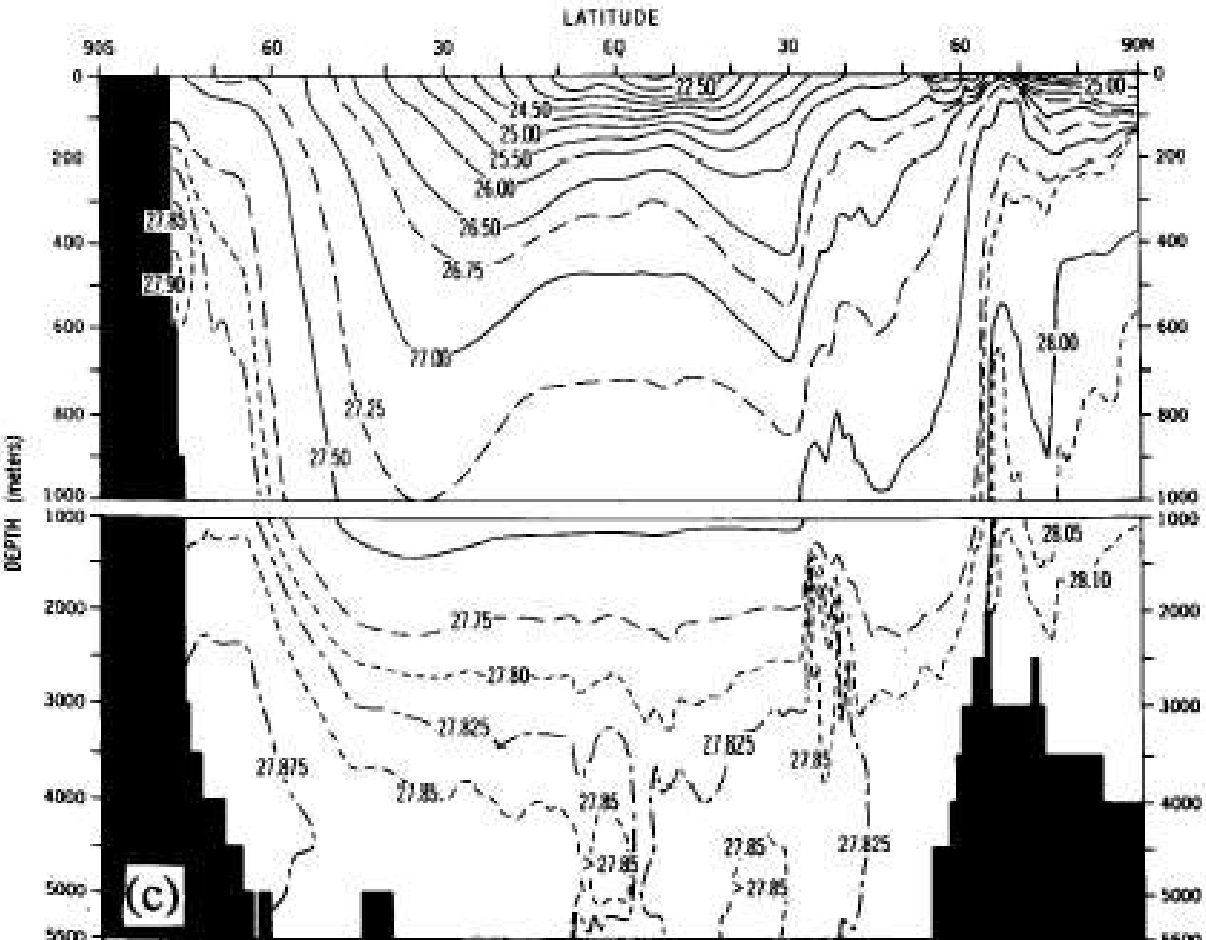


$40\text{-}90^0$ N and S: P>E

$15\text{-}40^0$ N and S: E>P

15^0S –15^0 N: P>E

Density structure: note that it ‘looks like’ the thermal structure, meaning that ***it is variations in temperature that mostly control variations in density***. One crucial exception is over the polar regions where salinity plays an important role in determining the the vertical structure of the oceanic density.



A sharp vertical density gradient is known as a ***pycnocline.***

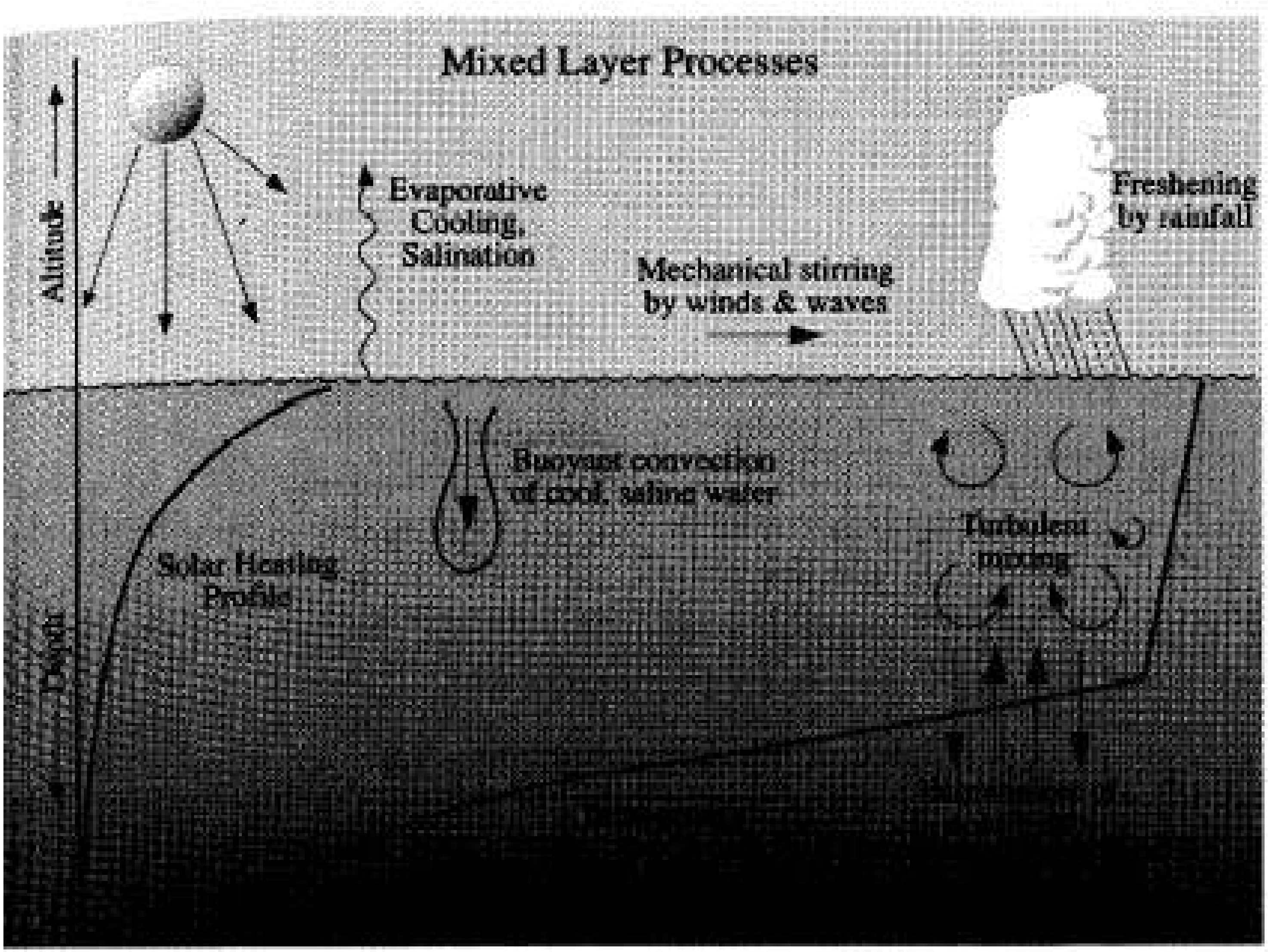
Potential density

ρ_t **–1000 (Kg/m^3)**

The oceanic mixed layer

Almost all of the solar energy flux into the ocean is absorbed in the top 100 m.
Blue and green are the most penetrating.
IR and near IR are absorbed in the top cm.
The depth to which V radiation penetrates depends on the amount and the optical properties of suspended organic matter (mainly plankton) that vary greatly with location (currents, local biologic productivity). The solar flux and heating rate in the ocean decrease exponentially with depth, according to the Lambert-Bouguet-Beer law.
Since solar heating affects several tens of m, while cooling by evaporation and SH transfer to the atmosphere occur at the surface, there must be an upward flux of energy in the upper ocean to maintain an energy balance between surface loss and subsurface heating.
Molecular diffuson plays a role only in the first cm.
Elsewhere, the flux is carried by **turbulent mixing** (aided by the supply of mechanical energy by the winds and their interaction with surface waves), **convective overturning** and **mean vertical motion *(upwelling* or *downwelling)***.
Storage and removal of heat from the ocean on time scales of less than 1 y are confined to the ***mixed layer*** *over much of the ocean.*

Mixed layer: ~ uniform T, S and ρ_t – rapid mechanical and thermal mixing



Depth of the mixed layer

It depends on the rate of buoyancy generation and the rate at which kinetic energy is supplied to the surface by winds.

- Buoyancy due to cooling/heating: if the surface is cooled very strongly (high latitude, fall and winter), cold, dense water is formed at the surface at a rapid rate and buoyancy forces will drive the convection (cold↓, warm↑). When the surface is cooled only weakly or actually heated (summer) the mixed layer becomes thinner and warmer.
- Buoyancy by effect of evaporation (salinity): can balance or overcome thermal stratification and favor mixing.
- Rainfall: decrease of surface density, reduces mixing.
- Turbulence from mechanical input by winds: can induce mixing even in the presence of stable stratification.

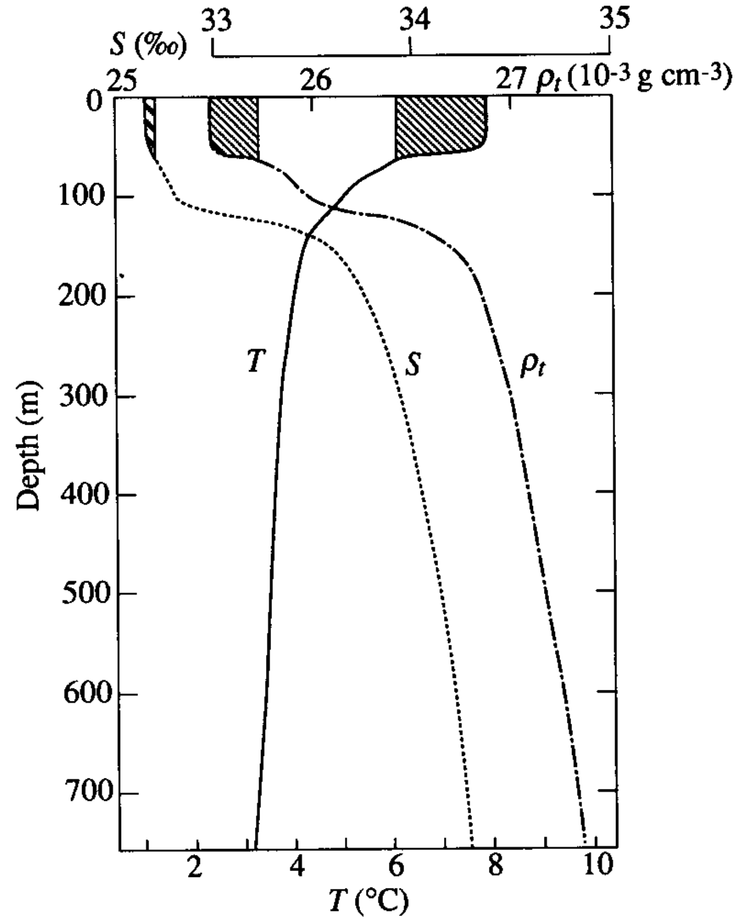
The depth of the mixed layer varies from a few meters in regions where subsurface waters upwell, as along the equator and in eastern boundary currents (along coastlines, see later), to the depth of the ocean in high latitude regions where cold, saline water sinks to the ocean bottom. The mixed layer is thin where the ocean is being heated and thick where the ocean gives up its energy to the atmosphere.

Example

ρ_t (10^{-3}g/cm^3)-1.

T, S and density at Ocean Station P (50N, 145W) on June 23, 1970
The thermocline and halocline are clearly visible, and the mixed layer is the first ~50m or so.

The hatched area shows the change since May 19, showing the effect of springtime warming and thinning of the mixed layer (T has become higher, ρ_t has decreased, the mixed layer has thinned).



Seasonal variation of the mixed layer

The mixed layer responds fairly quickly to changes in the surface wind and T, whereas the ocean below does not.
The mixed layer responds strongly to the annual cycle of insolation and surface weather.

It is warmest and thinnest in late summer, near the end of the period of greatest insolation and least intense stirring of the ocean by winds. After August (NH) the surface begins to cool, the storminess increases and the mixed layer begins to deepen and cool. It continues to do so troughout the winter and by the end of winter may extend to a depth of several hundred meters and merge smoothly into the **permanent thermocline** (present in all seasons).
During most of the rest of the year a **seasonal thermocline** with steep T gradients links the permanent thermocline with the base of the mixed layer.
In spring and summer this seasonal thermocline develops and the mixed layer becomes thinner and warmer.

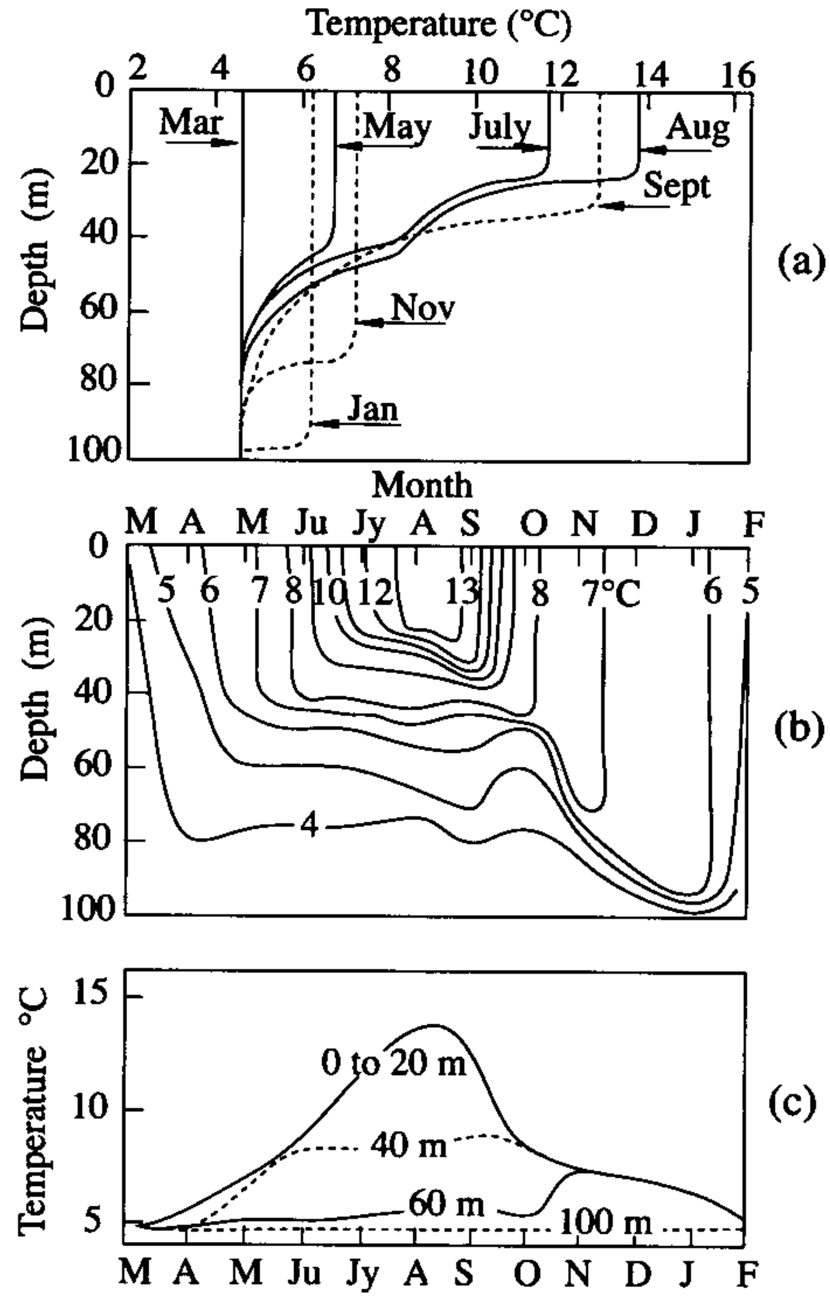
Seasonal variations in T are confined primarily to the mixed layer and the seasonal thermocline.

Example

Seasonal variations in the ocean surface - at a location in the North Pacific (50N, 145W):

(e) Vertical profiles of T by month
(b) T contours
(c) T at various depths versus time of the year

Note variations in the mixed layer depth and the thermal contrast between surface and deeper waters.



Wind-driven ocean circulations

Subtropical gyre circulation

NH Clockwise horizontal motions in the Atlantic and Pacific basins (SH: anticlockwise). Consists of:

•***Western boundary current*** (e.g. Gulf stream, Kuroshio in the NH, but there are also less defined and extensive counterparts in the SH) - relatively narrow (compared to width of basin) poleward current hugging the western basin boundary, transports warm waters polewards, from the tropics to the middle latit.

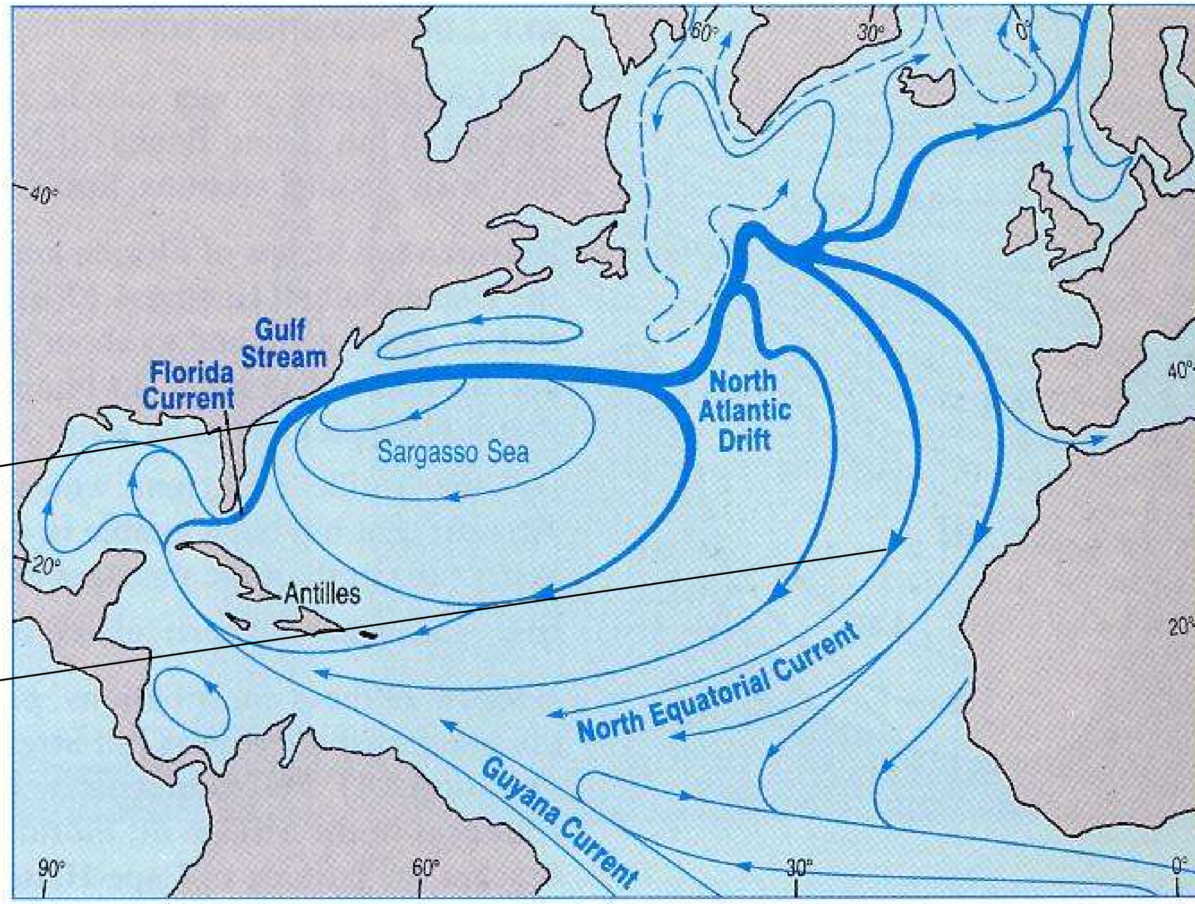
•Western boundary current separation region - where the current leaves the western edge and extends into the basin interior. This is where it meets the ***subpolar gyres*** (Oyashio in the N Pacific, Laborador in the N Atl) which brings with it cold water. The currents meander and form rings.

•The waters return equatorwards on the eastern side of the basin (***eastern boundary current***). The return flow is wider and slower-moving than the western boundary current, and brings cold water equatorwards. Their existence can be seen by looking the east-west contrast in sea surface temperature (SST) over a given latitude band. The waters near the east coast if the basin are the coldest, and it is a consequence of the ***upwelling*** - colder water from the interior of the ocean is brought to the surface at these locations, cooling the SST.

North Atlantic subtropical gyre circulation

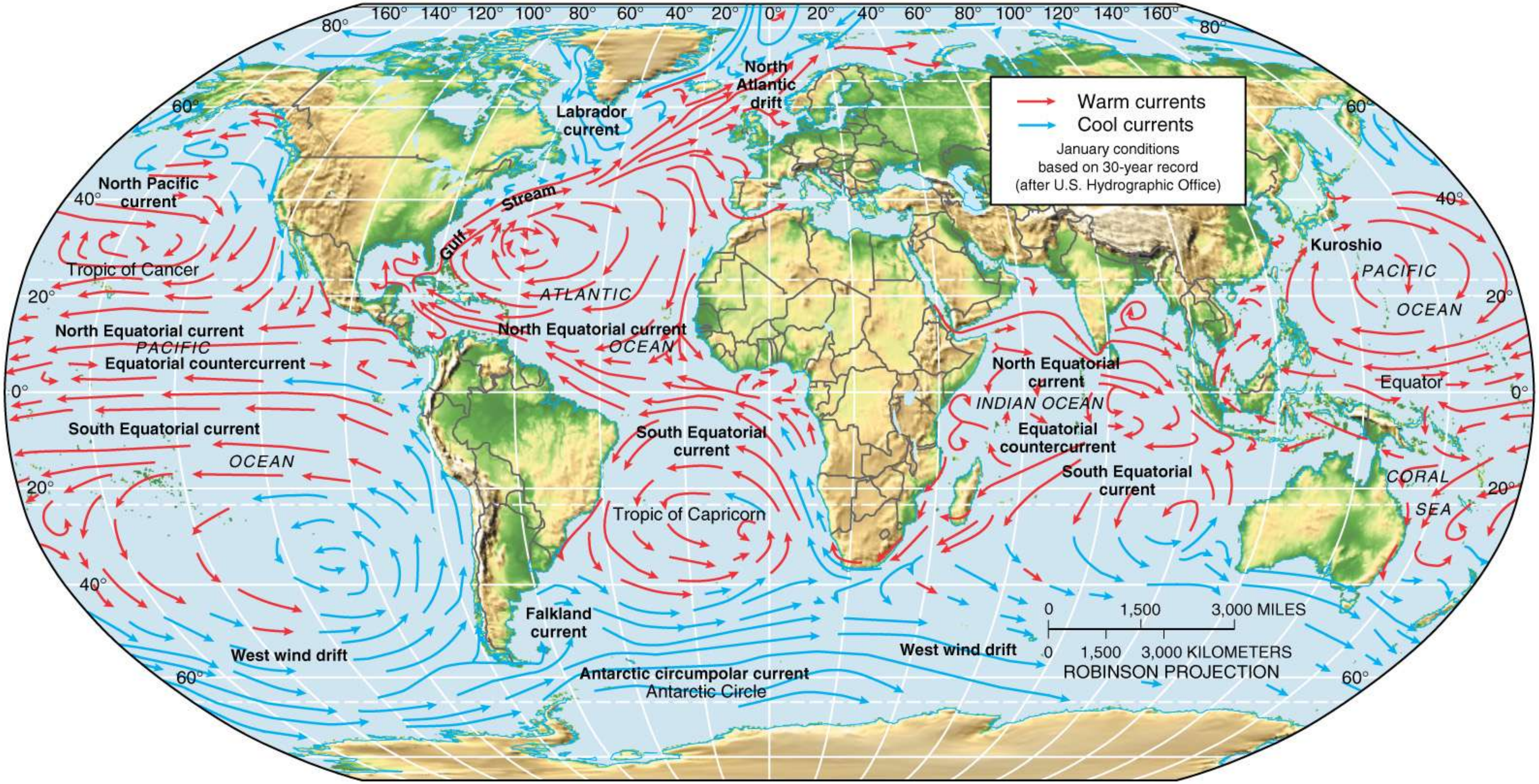
Western boundary current

Eastern ‘boundary current’



(a)

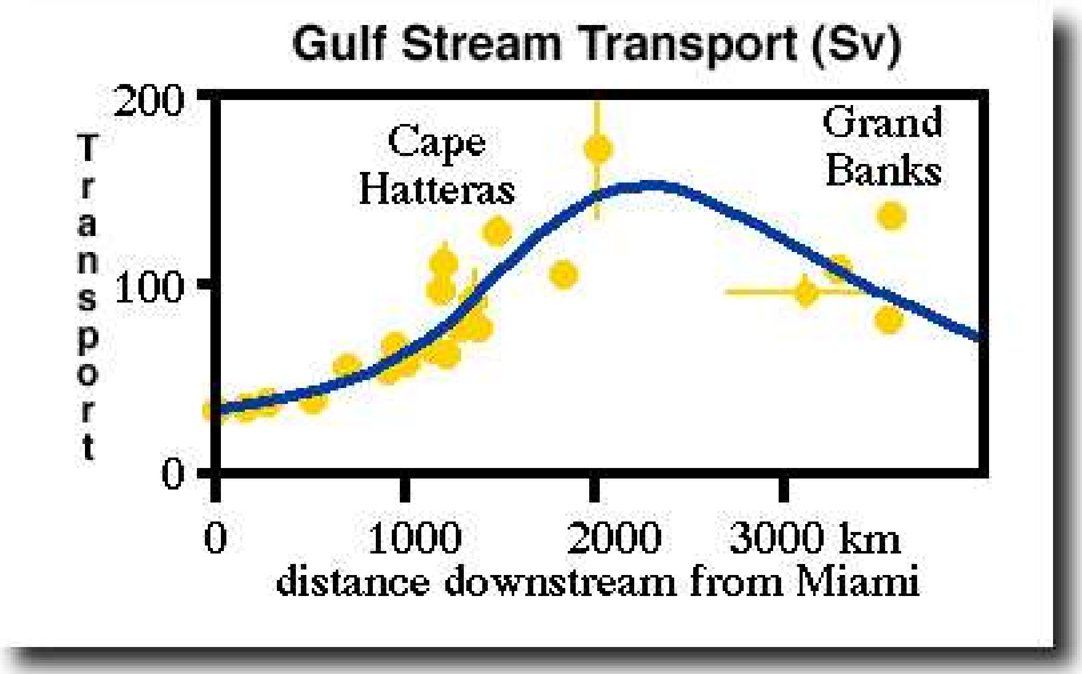
The wind-driven ocean circulation



Surface currents are arranged in coherent patterns with large circulations (gyres) occupying the major ocean basins. In addition, many narrow but persistent currents appear in time-averaged maps.

Gulf Stream transport

Measured in Sverdrups (Sv) = 10^6 m^3/s



Cape Hatteras: North Carolina, ~ 35^0N, 75^0W

Grand Banks: Newfoundland, ~ 45^0N, 55^0W

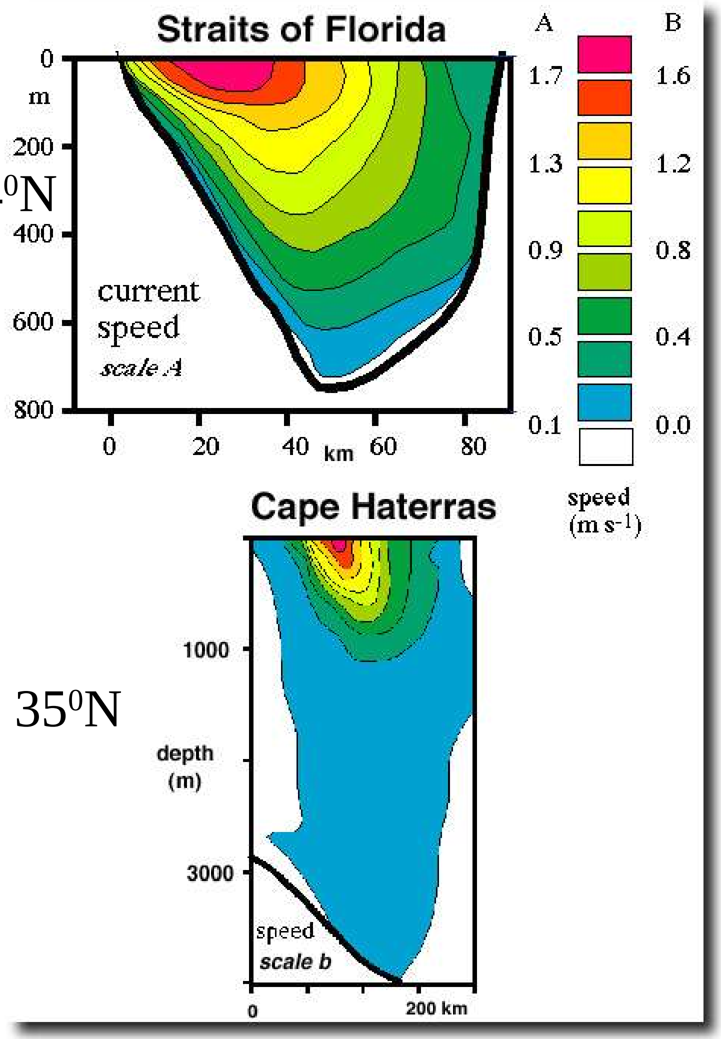
Note the increase in transport - because of *recirculation*

Gulf Stream velocity

Florida coast

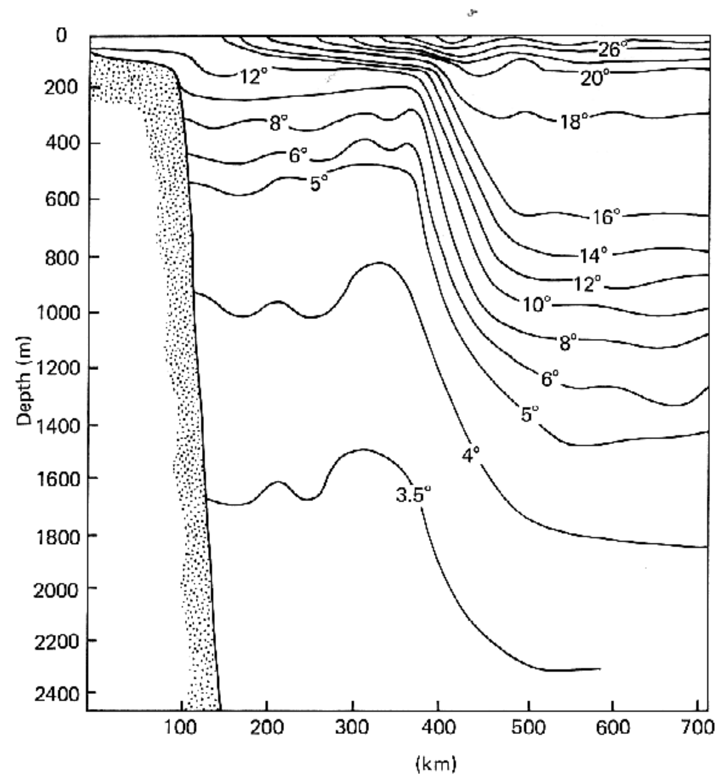
~ 24^0N

~ 35^0N



Source:http://kingfish.coastal.edu/marine/gulfstream/

Temperature cross-section



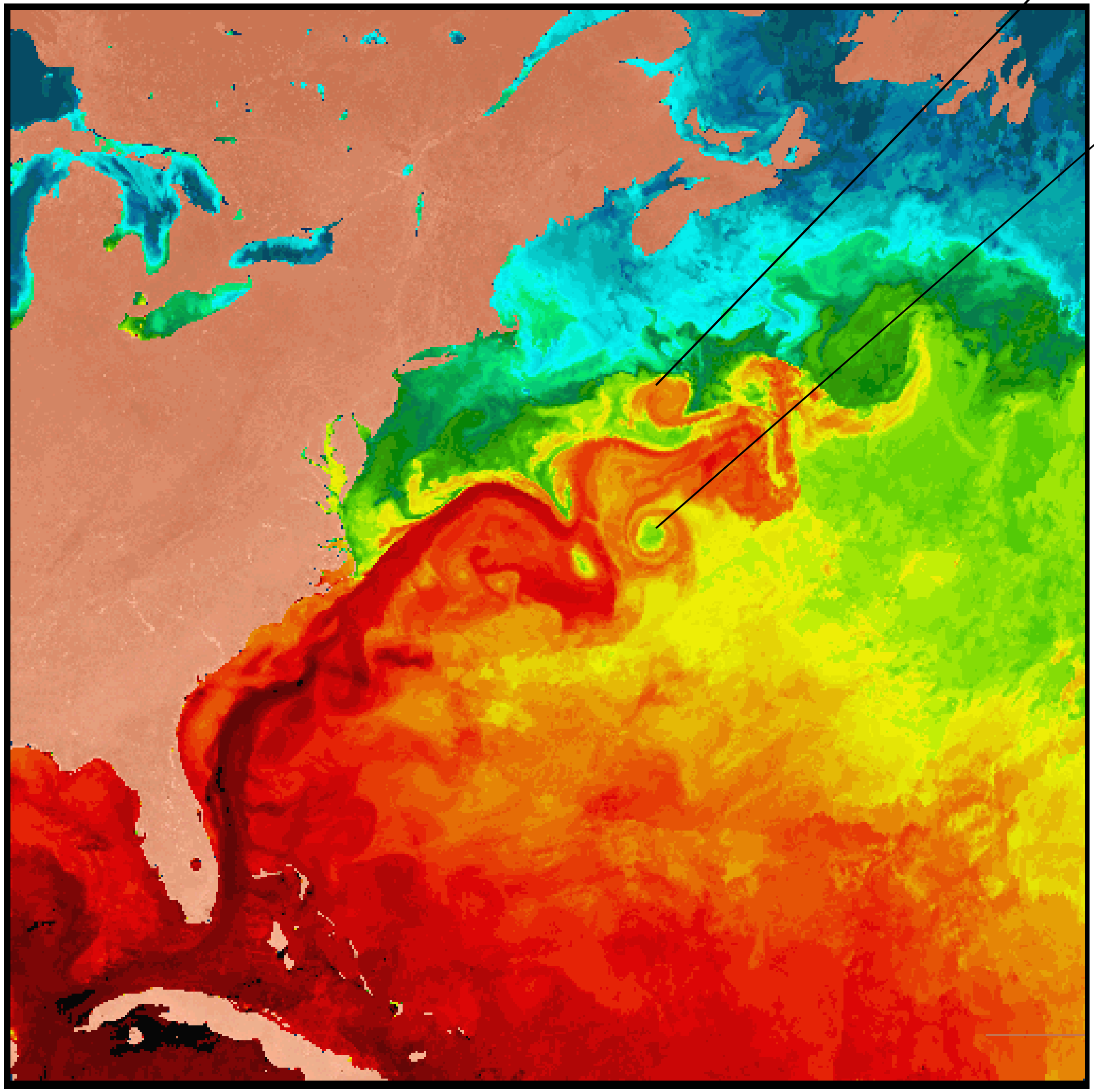
•Warmest waters, strongest velocities near the surface.

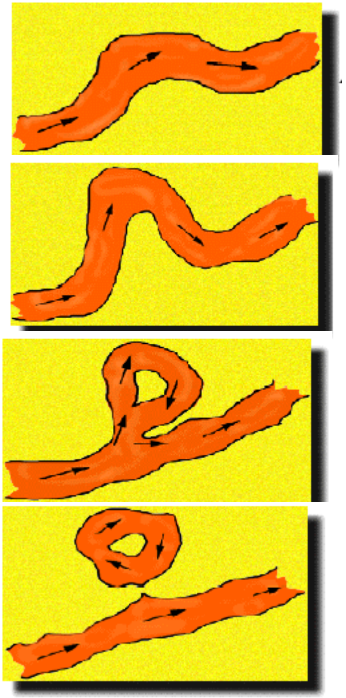
•Strong subsurface T gradient across the stream.

Gulf stream meanders
(typical size ~200km)

Warm core ring

Cold core ring





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